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**THz and sub-THz (MMW)-over-Fiber Data Links and Radar Technology**

**Ci-Ling Pan**  
**NATIONAL TSING HUA UNIVERSITY**

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**11/30/2016**  
**Final Report**

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**Arlington, Virginia 22203**  
**Air Force Materiel Command**

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<b>14. ABSTRACT</b> <p>Due to sub-THz millimeter wave (MMW) signals suffer substantial propagation loss in free-space or transmission line, and their inherent straight-line path of propagation affects connections and synchronization between the different parts of the communication system. A promising solution to overcome this problem is the millimeter wave over-fiber. The proposed research effort is to realize photonic-network compatible wireless data link at data rate up to 100 Gbit/s, and to explore a real-time MMW radar imaging system.</p>					
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THz and sub-THz (MMW)-over-Fiber Data Links and Radar Technology

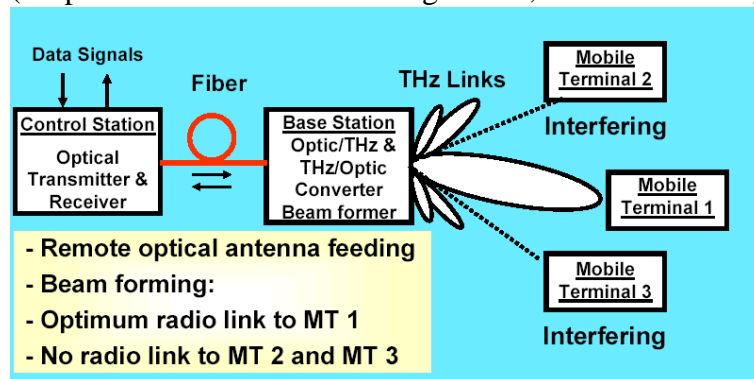
Ci-Ling Pan  
National Tsing Hua University  
Hsinchu, Taiwan

March 31, 2016  
(revised Nov 24, 2016)

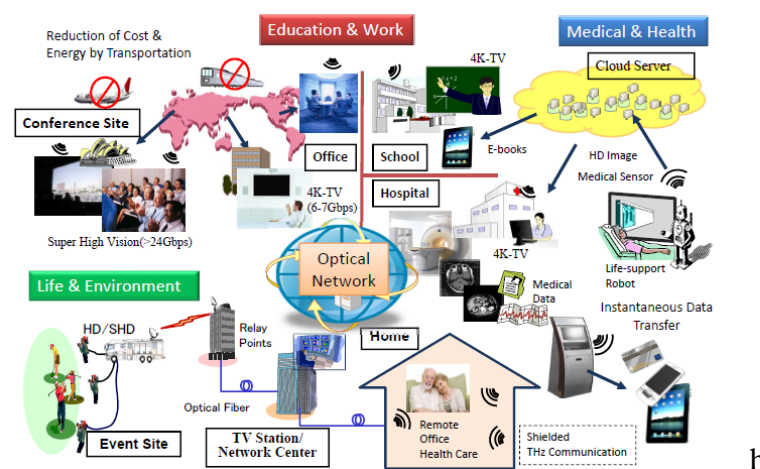
## 1. Overview

The information-intensive 21<sup>st</sup> century is sometimes referred as the Tera-era. Information needs be generated, stored, manipulated and transmitted to the global village at terabit rate, hopefully wirelessly. Unfortunately, such high-volume data transmission over air consumes radio bandwidth—lots of it. To meet this demand, the terahertz ( $1 \text{ THz} = 10^{12} \text{ Hz}$ ) wave band of the electromagnetic radiation must be explored. This frequency band represents an untapped region of the electromagnetic spectrum for the development of secure, short-range, high-data-rate wireless communications. The range limitation can be overcome by using the MMW-over-fiber (MOF) technique.

The following figures show respectively scenarios for military and other applications (adapted from slides of Prof. Nagatsuma, Osaka University).

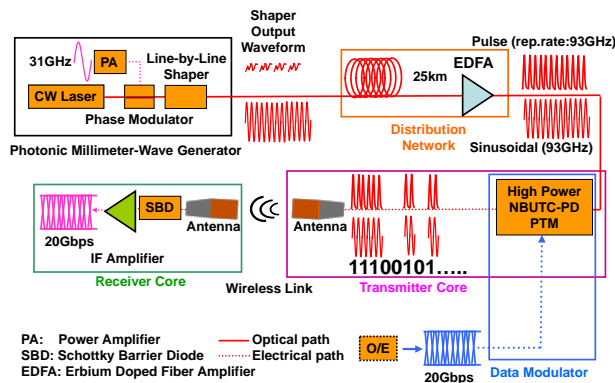


Secured THz links for  
military application

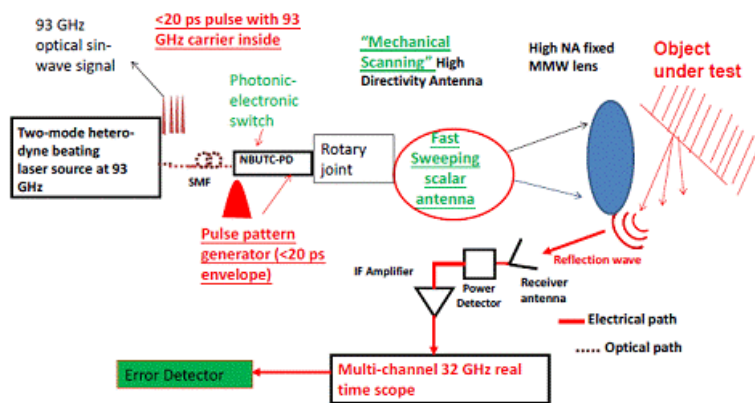


A broad range of  
applications  
envisioned for  
MMW-over-fiber  
Communication

Our team aims at photonic-network compatible wireless data link at data rate up to 100 Gbit/s. The technology can also be used to realize a real-time MMW Radar imaging system with ultra-high 3-D resolution. Model systems, as illustrated below, are based on high-power and broadband monolithic photonic THz/MMW transmitter (array) combined with photonic THz/MMW sources. Real-world system would be based on research and development of novel lasers, phased array of photonic transmitters, metamaterial and liquid-crystal-based functional quasi-optical components, etc.



The setup for optical-network-compatible high- data- rate W-band transmission system.



The setup for a real-time (sub-THz) MMW Radar

The following includes some examples of the most compelling terahertz-enabled communications opportunities (adapted from the web page of Teraphysics, <http://www.teraphysics.com/applications-by-industry.html>):

- Wireless delivery of data at 0.1 Tbit/s;
- Ultra-broad-band secure-bandwidth Radio-over-fiber communications in the battlefield environment: Terahertz wave's line-of-sight short range signals make it difficult for adversaries to intercept transmissions. Additionally, atmospheric attenuation naturally prohibits propagation to distant listening posts.
- High altitude secure communications, e.g., aircraft to satellite;
- Fiber-distribution of MMW-over-fiber signals inside business buildings and homes. High-volume data transmission can be sent to multiple locations simultaneously.
- Extension of the unallocated frequency bands currently available.
- Integrated MMW-over-fiber sensing and communication networks.

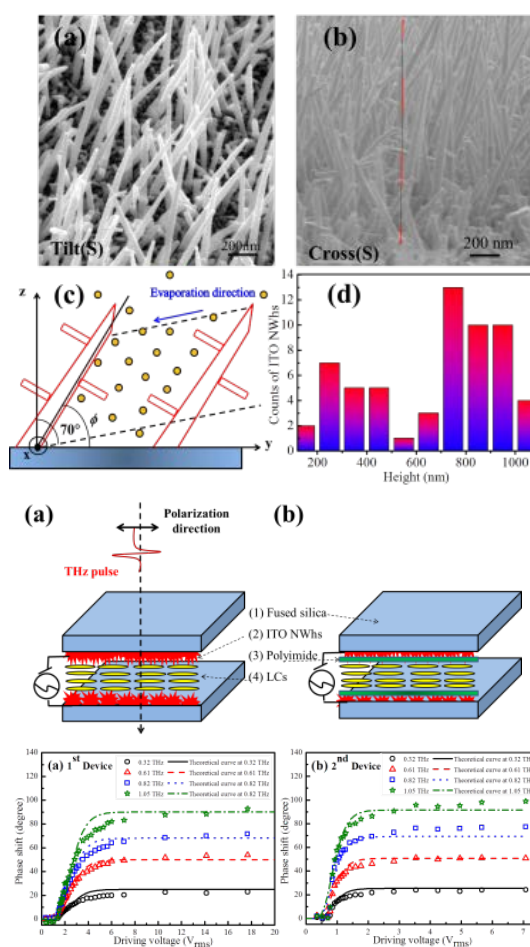
IEEE has already set up a THz Interest Group (IGthz for short) in the IEEE 802.15 WPAN Committee (<http://www.ieee802.org/15/pub/IGthz.html>). Admittedly, there are always doubts about the practicability of THz wireless communication (see for example, C. M. Armstrong, "The Truth About Terahertz," IEEE Spectrum, September 2012) in the atmosphere. Our approach, in fact, mitigates the problem. The goal, as discussed by IGthz, is not to transmit over very large distances, but to use THz waves for niche applications such as secured communication, nanocell and short-range fast downloads wirelessly at an access point. Combining optical and THz technology is the key.

In conclusion, it is conceivable to build photonic-network compatible sub-THz (MMW) links at data rates approaching 100 Gb/s. This would be of interests to niche applications such as

high-speed access point, secured military communication and in cloud data centers for interconnecting servers wirelessly. Such technology can also be leveraged for quasi-real-time photonic-network-compatible 3D imaging radar. Applications include remote, distributed diagnostic medical imaging; people imaging and baggage scanning for the detection of concealed weapons and explosives and through-wall 3D imaging for covert surveillance and reconnaissance. This project holds the future of a new multi-billion vertically integrated high-tech industry. Near term prospects include the Wireless High-definition (WiHD) technology at home and UWB Telemedicine.

## 2. Research Highlights

- **Liquid crystal terahertz phase shifters with functional indium-tin-oxide nanostructures for biasing and alignment**



We constructed a THz liquid crystal (LC) phase shifter with Indium Tin Oxide (ITO) nanowhiskers (NWs). Phase shift exceeding  $\pi/2$  at 1.0 THz was achieved in a 517  $\mu\text{m}$  thick cell. The phase shifter exhibits high transmittance ( $\sim 78\%$ ). The driving voltage required for quarter-wave operation is as low as 5.66V (rms), compatible with complementary metal-oxide semiconductor (CMOS) and thin-film transistor (TFT) technologies. Indium Tin Oxide (ITO) nanowhiskers (NWs) obliquely evaporated by electron-beam glancing angle deposition can serve simultaneously as transparent electrodes and alignment layer for liquid crystal devices in the terahertz frequency range.

- Appl. Phys. Lett., Vol. 104, No. 14, art. 141106, April 7, 2014.
- Opt. Lett., Vol. 39, No. 8, pp. 2511-2513, Apr. 15, 2014.

**Impact: A novel tunable phase shifter with record-high transmittance ( $\sim 78\%$ ) and low driving voltage ( $\sim 5.66\text{V}$  (rms) for quarter-wave operation)**

**Industrial interests: post-5G wireless communication, imaging radar, THz instrumentation, biomedical imaging (THz band)**

- **Coding for stable transmission of W-band radio over-fiber system using direct-beating of two independent lasers**

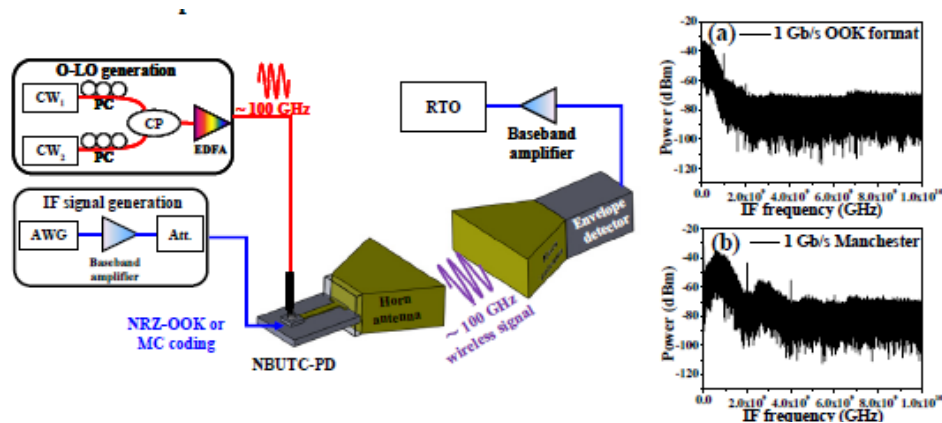
We demonstrate experimentally Manchester (MC) coding based W-band (75 – 110 GHz) radio-over-fiber (ROF) system to reduce the low frequency-components (LFCs) signal distortion generated by two independent low-cost lasers using spectral shaping.

*Opt. Express*, Vol. 22, Issue 21, pp. 26092-26097, Oct. 16, 2014. [DOI: [10.1364/OE.22.026092](https://doi.org/10.1364/OE.22.026092)]

**Impact:**

- At higher photocurrent ( $> 4.5$  mA) for the photonic THz transmitter, Bit-Error-Rate (BER) performance by the Manchester coding is better than the system that uses conventional NRZ-OOK coding scheme.
- A low-cost and higher performance W-band ROF system is achieved using two independent low-cost lasers and spectral shaping.

**Industrial interests: post-5G wireless communication**



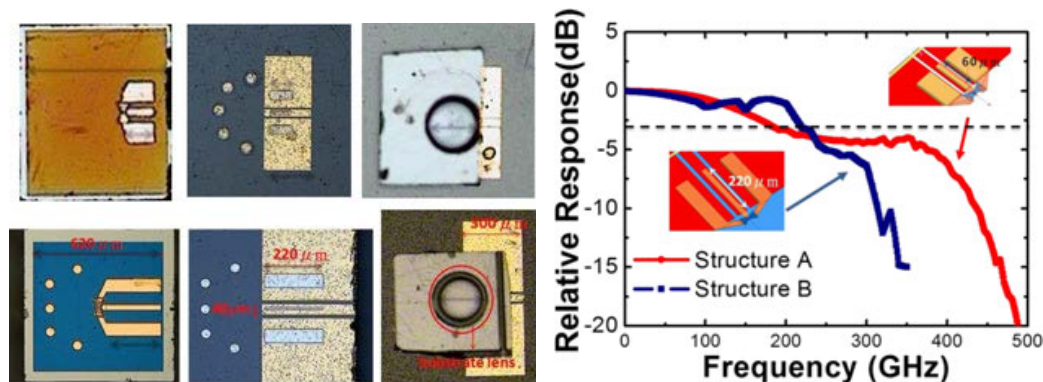
- **Photonic High-Power sub-MMW (up to 315 GHz) Signal Generation by Using Ultrafast Photodiode and a High-Repetition-Rate Femtosecond Optical Pulse Train Generator**

A femtosecond optical short-pulse generator with extremely high repetition rate (160 GHz) and pulsewidth as short as 285 fs. With this novel source, we generated high MMW power (+7.8 dBm) with an effective 120% optical modulation depth at 160 GHz directly from the near ballistic untravelling carrier photodiodes (NBUTC-PD). Later, this is extended to  $\sim 0.4$  THz with an average power of 1 mW. The proposed device structure also exhibits excellent bias modulation characteristics, i.e., extremely small driving voltage (0 to  $-1$  V) with  $> 30$  dB swing of sub-THz power.

*J. Sel. Top. Quantum Electron.*, Vol. 20, No. 6, art. 3803507, Nov/Dec 2014. [DOI: [10.1109/JSTQE.2014.2329940](https://doi.org/10.1109/JSTQE.2014.2329940)]

*IEEE/OSA J. Lightwave Technol.*, vol. 34, no. 4, pp. 1387-1397, February 15, 2016. [DOI: [10.1109/JLT.2015.2503778](https://doi.org/10.1109/JLT.2015.2503778)]





**Impact:** A photonic sub-THz wireless linking with extremely high data rate (>25 Gbit/s) and reasonable wireless linking distance (several meters) can be realized.

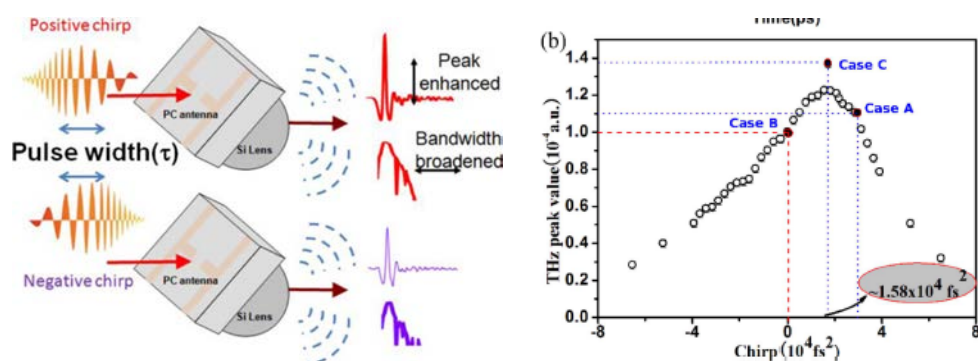
**Industrial interests:** post-5G wireless communication

- Enhanced THz signal Generation by pre-chirped pulse excitation

Nearly 3-dB enlargement on peak amplitude of THz radiation accompanied by broadened bandwidth is achieved with positively chirped pulse excitation of a LT-GaAs photoconductive antenna. It is shown that the laser with short pulsewidth is responsible for the broadening of THz bandwidth, whereas the peak amplitude of the THz pulse relies strictly on lengthened carrier lifetime from appropriately chirped exciting pulse.

*Appl. Phys. Lett.*, Vol. 104, No. 17, art. 172105, April 7, 2014. April 28, 2014. [DOI: [10.1063/1.4875027](https://doi.org/10.1063/1.4875027)]

*IEEE Trans. THz Sci. & Technol.*, vol. 6, No. 2, pp. 253-261, March, 2016. [DOI: [10.1109/TTHZ.2016.2525819](https://doi.org/10.1109/TTHZ.2016.2525819)]



**Impact:** This investigation has provided guidelines to design a proper chirp arrangement for the exciting laser pulse in a THz-TDS system for enhancing the amplitude and broadening the spectral linewidth of the THz radiation. The pre-chirped pulse management greatly extends the applicability of the generated THz pulse for versatile diagnostic systems.

**Industrial interests:** THz spectroscopy and imaging



### 3. Publications

#### A. Archived journals:

- Rone-Hwa Chou, Chan-Shan Yang, and Ci-Ling Pan\*, “Correlation Approach to Propagation of Terahertz Pulse in Dielectrics for Material Characterization,” *IEEE Photon. Technol. Lett.*, Vol. 25, No. 14, pp. 1389-1391, July 15, 2013 [DOI: [10.1109/LPT.2013.2265405](https://doi.org/10.1109/LPT.2013.2265405)].
- Chan-Shan Yang, Chan-Ming Chang, Po-Han Chen, Peichen Yu, and Ci-Ling Pan\*, “Broadband Terahertz Conductivity and Optical Transmission of Indium-Tin-Oxide (ITO) Nanomaterials,” *Optics Express*, Vol. 21, Iss. 14, pp: 16670–16682, July 15, 2013. [DOI: [10.1364/OE.21.016670](https://doi.org/10.1364/OE.21.016670)].
- Rone-Hwa Chou, Chan-Shan Yang, and Ci-Ling Pan, “Effects of pump pulse propagation and spatial distribution of bias fields on terahertz generation from photoconductive antennas,” *J. Appl. Phys.*, Vol.114, Issue 4, art. 043108, July 28, 2013. [DOI: [10.1063/1.4816561](https://doi.org/10.1063/1.4816561)]
- Chan-Shan Yang, Mao-Hsiang Lin, Chia-Hua Chang, Peichen Yu, Jia-Min Shieh, Chang-Hong Shen, Osamu Wada, and Ci-Ling Pan\*, “Non-Drude Behavior in Indium-Tin-Oxide Nanowhiskers and Thin Films Investigated by Transmission and Reflection THz Time-Domain Spectroscopy,” *IEEE J. Quantum Electron.*, Vol. 49, No. 8, pp. 677-690, August, 2013. [DOI: [10.1109/JQE.2013.2270552](https://doi.org/10.1109/JQE.2013.2270552)]
- Chan-Shan Yang, Tsung-Ta Tang, Ru-Pin Pan, Peichen Yu, and Ci-Ling Pan\*, “Liquid crystal terahertz phase shifters with functional indium-tin-oxide nanostructures for biasing and alignment,” *Appl. Phys. Lett.*, Vol. 104, No. 14, art. 141106, April 7, 2014. [DOI: [10.1063/1.4871255](https://doi.org/10.1063/1.4871255)]
- Chan-Shan Yang, Tsung-Ta Tang, Po-Han Chen, Ru-Pin Pan, Peichen Yu, and Ci-Ling Pan\*, “Voltage-controlled liquid-crystal terahertz phase shifter with indium–tin–oxide nanowhiskers as transparent electrodes,” *Opt. Lett.*, Vol. 39, No. 8, pp. 2511-2513, Apr. 15, 2014. [DOI: [10.1364/OL.39.002511](https://doi.org/10.1364/OL.39.002511)].
- Chao-Kuei Lee, Yuan-Yao Lin, Sung-Hui Lin, Gong-Ru Lin and Ci-Ling Pan, “Chirped-pulse manipulated carrier dynamics in low-temperature molecular-beam-epitaxy grown GaAs,” *Appl. Phys. Lett.*, Vol. 104, No. 17, art. 172105, April 7, 2014. April 28, 2014. [DOI: [10.1063/1.4875027](https://doi.org/10.1063/1.4875027)]
- Jiun-Yu Sung, Kai-Teng Cheng, Chi-Wai Chow,\* Chien-Hung Yeh, and Ci-Ling Pan, “A scalable and continuous-upgradable optical wireless and wired convergent access network,” *Opt. Express*, Vol. 22, Issue 11, pp. 12779-12784, June 2, 2014. [DOI: [10.1364/OE.22.012779](https://doi.org/10.1364/OE.22.012779)]
- Jim-Wein Lin, Jhih-Min Wun, Jin-Wei Shi, Ci-Ling Pan, “All-Optical Generation and Switching of Few-Cycle Millimeter-Wave Pulses,” *J. of Infrared, Millimeter, and Terahertz Waves*, Vol. 35, Issue 10, pp. 813-822, October 2014. [DOI: [10.1007/s10762-014-0089-5](https://doi.org/10.1007/s10762-014-0089-5)]
- L. G. Yang, J. Y. Sung, C. W. Chow, C. H. Yeh, K. T. Cheng, J. W. Shi, and C. -L. Pan, “Coding for stable transmission of W-band radio-over-fiber system using direct-beating of two independent lasers,” *Opt. Express*, Vol. 22, Issue 21, pp. 26092-26097, Oct. 16, 2014. [DOI: [10.1364/OE.22.026092](https://doi.org/10.1364/OE.22.026092)]
- Jhih-Min Wun, Hao-Yun Liu, Cheng-Hung Lai, Yi-Shiun Chen, S.-D. Yang, C.-B. Huang, Ci-Ling Pan, J. E. Bowers, “Photonic High-Power Sub-THz

Signal Generation by using Ultra-Fast Photodiode and a High-Repetition-Rate Femtosecond Optical Pulse Train Generator,” *J. Sel. Top. Quantum Electron.*, Vol. 20, No. 6, art. 3803507, Nov/Dec 2014. [DOI: [10.1109/JSTQE.2014.2329940](https://doi.org/10.1109/JSTQE.2014.2329940)]

- Chan-Shan Yang, Chun Kuo, Chiu-Chun Tang, J. C. Chen, Ru-Pin Pan, and Ci-Ling Pan\* "Liquid-crystal Terahertz Quarter-wave Plate Using Chemical-vapor-deposited Graphene Electrodes," *IEEE Photonics Journal*, Vol. 7, No. 6, art. 2200808, December 2015. [DOI: [10.1109/JPHOT.2015.2504960](https://doi.org/10.1109/JPHOT.2015.2504960)]
- Jhih-Min Wun, Hao-Yun Liu, Yu-Lun Zeng, Shang-Da Yang, Ci-Ling Pan, ChenBin Huang, and Jin-Wei Shi, "Photonic High-Power Continuous Wave THz-Wave Generation by Using Flip-Chip Packaged Uni-Traveling Carrier Photodiodes and a Femtosecond Optical Pulse Generator," *IEEE/OSA J. Lightwave Technol.*, vol. 34, no. 4, pp. 1387-1397, February 15, 2016. [DOI: [10.1109/JLT.2015.2503778](https://doi.org/10.1109/JLT.2015.2503778)]
- Chao-Kuei Lee\*, Yuan-Yao Lin\*, Gong-Ru Lin, Chung-Lun Wu, Tsung-Han Wu, Chin-Rong Chuang, and Ci-Ling Pan, "Pre-chirped pulse excitation enhanced Terahertz radiation," *IEEE Trans. THz Sci. & Technol.*, vol. 6, No. 2, pp. 253-261, March, 2016. [DOI: <http://dx.doi.org/10.1109/TTHZ.2016.2525819>]

#### B. Book chapters

- Ci-Ling Pan and Jin-Wei Shi, "Ultrawide-Band Sub-THz Photonic Wireless Links," in *Microwave Photonics*, ed., C. H. Lee, 2nd ed., CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA, 2013, pp. 97-124. Print ISBN: 978-1-4665-0286-4, [DOI: [10.1201/b13886-4](https://doi.org/10.1201/b13886-4)]
- Ci-Ling Pan, Alexey Zaytsev, Chih-Hsuan Lin, Yi-Jing You, and Chi-Luen Wang, "Progress in Short-Pulse Yb-doped Fiber Oscillators and Amplifiers," Chapter 3, in *The Current Trend of Optics and Photonics, Topics in Applied Physics, Vol. 129*, pp. ed., C. C. Lee, Springer Netherlands, 2015, pp. 61-100, Print ISBN: 978-94-017-9391-9. [DOI: [10.1007/978-94-017-9392-6\\_3](https://doi.org/10.1007/978-94-017-9392-6_3)]
- Ci-Ling Pan, Alexey Zaytsev, Yi-Jing You and Chih-Hsuan Lin, "Fiber-laser-generated Noise-like Pulses and Their Applications," Chapter 10, pp. 211-243, in *FIBER LASER*, ed. Mukul Paul, InTech, Rijeka, Croatia, 2016, ISBN: 978-953-51-4615-5 [DOI: <http://dx.doi.org/10.5772/61856>], Available from: <http://www.intechopen.com/books/fiber-laser/fiber-laser-generated-noise-like-pulses-and-their-applications>.
- Ci-Ling Pan, Chih-Hsuan Lin, Chan-Shan Yang, and Alexey Zaytsev, "Laser Ablation of Polymethylmethacrylate (PMMA) by Phase-controlled Femtosecond two-color Synthesized Waveforms," to appear in *LASER ABLATION*, ed., Dongfang Yang, InTech, Rijeka, Croatia, 2016, ISBN 978-953-51-4892-0
- Ci-Ling Pan, Chan-Shan Yang, Ru-Pin Pan and Peichen Yu, "Nanostructured Indium Tin Oxides and other Transparent Conducting Oxides: Characteristics and Applications in the THz Frequency Range," to appear in *Terahertz Spectroscopy - Cutting Edge Technology*, ed., Jamal Uddin, InTech, Rijeka, Croatia, 2016, ISBN 978-953-51-4936-1.

#### 4. Invited talks:

- C. L. Pan, J. W. Lin, J. M. Wun, and J. W. Shi, "Toward Single-Cycle MMW Pulse Generation by Optoelectronic Switching of a High-Speed Photonic-Transmitter-Mixer," **invited talk**, presented at the 6th IEEE/international Conference on Advanced Infocomm Technology, July 6-9, 2013, Hsinchu, Taiwan.
- Ci-Ling Pan, "Broadband terahertz conductivity and optical transmission of indium-tin-oxide (ITO) nanomaterials," **SPIE Traveling Lecture**, Center for Optoelectronics and Optical Communications, University of North Carolina, Charlotte, North Carolina, USA, Oct. 1, 2013.
- Ci-Ling Pan and Ru-Pin Pan, "Characterization and Applications and Liquid Crystals in the THz Frequency Range," **invited talk**, presented in the Annual Meeting of the Chinese Physical Society, Sept. 11-14, Harbin, China.
- Ci-Ling Pan, "Liquid Crystal THz Optics: a tutorial overview," **OSA Traveling Lecture**, Nanjing University, Sept. 16, 2014, Nanjing, China.
- Ci-Ling Pan, "Recent advances in millimeter-wave photonic wireless links for very high data rate communication," **invited talk**, Wuhan Optoelectronics Forum, Oct. 24, 2014, Wuhan, China.
- Ci-Ling Pan, "Towards THz wireless links in the 21th century, **invited talk**, presented in the Special Symposium for International Year of Light, The annual meeting of the Physical Society of Republic of China (PSROC), Jan. 29, 2015, National Tsing Hua University, Hsinchu, Taiwan.
- Ci-Ling Pan, "Liquid Crystal THz Photonics with Indium Tin Oxide nanowhiskers and graphene as functional electrodes," **invited talk** presented at OE128: Emerging Liquid Crystal Technologies X, part of Photonics West, February 10, 2015, San Francisco, CA, USA., Proc. SPIE 9384, Emerging Liquid Crystal Technologies X, 93840Q (March 11, 2015); [doi:[10.1117/12.2079324](https://doi.org/10.1117/12.2079324)]
- Ci-Ling Pan, "Selected topics on Photonics-Technologies-enabled THz Wireless Communications," **invited talk**, presented at the 2015 Cross-Strait Forum on Optoelectronics, June 14-16, 2015, Wuhan, China.
- Ci-Ling Pan and Chan-Shan Yang, "transparent Conducting Oxides for THz Applications," **invited talk**, presented at The 8th International Photonics and OptoElectronics Meetings (POEM 2015), OSA Topical Meeting on Optoelectronic Devices and Integration (ODEI), June 16-19. Wuhan, China, paper OTB.1, [doi:[10.1364/OEDI.2015.OT2B.1](https://doi.org/10.1364/OEDI.2015.OT2B.1)]
- Ci-Ling Pan, Chan-Shan Yang, and Ru-Pin Pan, "Transparent Conducting Oxides: Terahertz properties and applications," **invited talk**, presented at the Joint Symposium of the 6<sup>th</sup> International Symposium on Terahertz Nanoscience (Teranano-6) and the 3<sup>rd</sup> Symposium on Microwave/THz Science and Applications (MTSA 2015), June 30 - July 4, 2015, Okinawa, Japan.
- Ci-Ling Pan, THz spectroscopic studies of indium-tin-oxide (ITO) nanomaterials (and other TCOs)," **plenary talk**, presented at Light Conference: International Conference on Micro/Nano Optical Engineering – Taiwan, Tainan, Taiwan, Aug. 10-14, 2015.
- Ci-Ling Pan, "Nanostructured Transparent Conducting Oxides: Characteristics and Applications in the THz Frequency Range," ASu2-3D.1, **Tutorial** presented at ACP 2015, Asia Communications and Photonics

Conference, Hong Kong, Nov. 19-23, 2015.

- Ci-Ling Pan, “Optimization of Photoconductive-Antenna-Based THz Time-Domain Spectroscopic Measurements by Pulse Shaping,” paper AS2H.1, **invited talk**, presented at the 2016 Asia Communication and Photonics Conference, Wuhan, China, Nov. 2-5, 2016.

#### 5. Awards and Recognitions:

- Outstanding Scholar Award, Foundation for the Advancement of Outstanding Scholarship, Taipei, Taiwan (2012-2015)
- Outstanding Alumni Award, Tunghai University, Taichung, Taiwan (2013)
- Member, Asia-Pacific Academy of Materials (2013)
- Member, Commission D (Electronics and photonics), Union Radio-Scientifique Internationale or URSI (2013 to date).
- Distinguished Lecturer, IEEE Electron Devices Society (2015 -)
- Chun-Yi Tsai, Yuan-Ru Lin, Chan-Shan Yang, Wei-Jan Chen, and Ci-Ling Pan, “Observation of Coherence Effect of Two-Color Exciting Nonlinear Frequency Conversion in Argon” , 2014 Annual Meeting of the Physical Society of Republic of China, National Chung Hsing University, Taichung, , January 21-23, 2014, paper P2-OE-046. (**Best Student Poster Paper Award**)
- W. C. Lin, H. Y. Yao, T. H. Chang and C. Kuo, C. L. Pan, “Characterizing the complex permittivity and permeability using THz time-domain spectroscopy,” *ibid.*, paper P2-OE-166. (**Best Student Poster Paper**)
- Chan-Shang Yang, Best Ph.D. Thesis Award, Taiwan Photonics Society, 2014
- Chan-Shang Yang, Bor-Ueo Chen Memorial Scholarship Award, Photonic Society of Chinese Americans (PSC), March 25, 2015.
- Yi-Jing You, Incubic Milton Traveling Grant, Optical Society of America, 2015
- Yi-Jung Wang, Yi-Jing You, Alexey Zaytsev, Chih-Hsuan Lin, Ci-Ling Pan, “Mode-locked Yb-doped fiber laser based on saturable absorber,” The annual meeting of the Physical Society of Republic of China (PSROC), National Sun Yat-sen University, Kaohsiung, January 25-27, 2016, paper 2016-Tue-P1-OE-101, (**Best Student Poster Paper Award**)

#### 6. Research Funds

Following are Prof. Pan’s funded proposals and ongoing projects besides the project supported by AFOSR. The annual budget is around 500K USD.

##### **[1] Fundamental and Applied Studies for advanced Sub-THz (Millimeter-Wave) Imaging Radar (NSC, Aug. 1, 2012-July 31, 2015)**

To date, we have demonstrated W-band (0.1 THz or 100 GHz) Radio-over-fiber communication with data rate beyond 20 Gbit/s. The key technologies are (1) photonics-based W-band MMW source and the sub-THz (MMW) photonic transmitter. In this work, we will further develop the source such that higher-power MMW generation at operation up to the J-band (200-400 GHz) with dynamic adaptive control would be possible. Such sources will be used for the MMW imaging Radar and sensing applications. We will also look into the potential of multiple-input-multiple-output (MIMO) Radar convergence with optical-frequency-division-multiplexed MIMO

communication so that an integrated platform for both communication and radar could be established for cost and power consumption reduction. We will also conduct diagnostics on high-speed photodiodes and photonic transmitters developed by our collaborators.

**[2] Table-top Sub-Single-Cycle Attosecond Laser Sources (II) (NSC, August 1, 2012 - July 31, 2015)**

Attosecond ( $1 \text{ as} = 10^{-18} \text{ sec}$ ) science, because its potential for unlocking the ultrafast dynamics in the nano-world, is generally recognized as one of the frontier areas in science today. In our on-going work, we have successfully constructed a sub-femtosecond (attosecond) coherent light source by starting from a single nanosecond laser and phase lock the cascaded harmonics generated by second-order nonlinear optical processes. This source will be fine-tuned such that a time-resolution of several tens of attosecond can be realized. We proposed to construct an apparatus for the generation of higher-order harmonics (HHG) assisted by surface plasmon polaritons and the characterization of the synthesized pulse train. Taking advantage of the capability of the present source for amplitude and phase control of the individual harmonics, an optimized electric waveform for driving the electrons for highly efficient HHG should be possible, which was proposed theoretically previously. Phase effects should also be evident even for harmonic generation in the perturbative regime ( $n \ll 9$ ). More efficient generation of such lower harmonics should be possible. The synthesis of first nine harmonics should already allowed us to generate transform-limited pulses shorter than 200 as, with wavelength extending to the VUV region, i.e., 118 nm. More precise synthesis of arbitrary light waveforms should also be possible with 9 components as opposed to five in the present source. We also intend to investigate the feasibility of material processing, e.g., ablation, with the present source, based on preliminary results.

**[ 3 ] Research and Development of Advanced Fiber Laser Systems and Their Applications, PI (NSC Industrial co-op with Cleverwave Corp. and POFC, June 1. 2013- May 31, 2016)**

Laser machining and processing of materials are among the most important applications of the laser. Taiwan has a robust laser processing industry. Regretfully, almost all of the high-power lasers used in the processing centers are imported. Lasers of different specifications are needed for versatile applications ranging from precision resistor trimming, scribing for the solid-state lighting and solar cell industry, laser annealing and activation. Up to now, we have successfully developed 10-ps-class high-average-power ( $> 50 \text{ W}$  at 1 ~~closed~~ fiber laser systems and green output  $> 5 \text{ W}$ . In this follow-up project, we propose to develop high-pulse-energy ns, ps and fs Yb-fiber lasers for the above mentioned applications. Through efficient nonlinear frequency conversion, green laser which wavelength is 532nm and UV laser output at 266 nm will be generated as well. Critical components such as fiber adaptors developed in the project should also be useful in fiber communication and sensing system.

**[ 4 ] Functional THz Photonic Elements and their Applications (MOST, Aug. 1, 2015-July 31, 2018)**

We propose to study terahertz functional photonic component and modules for the photonics-enabled post 5G network. These would be potentially useful for applications in (i) multi-gigabit THz wireless-over-fiber communication services; (ii) photonic generation of sub-millimeter waves and signal processing; (iii) photonics-based high-spatial-resolution 3D imaging Radar.

**[ 5 ] Generation and applications of Intense Coherent THz Radiation  
(MOST, August 1, 2015 - July 31, 2016)**

In the past decades, we have witnessed tremendous progress in the science and technology of the THz ( $1\text{THz} = 10^{12}\text{ Hz}$ ) or sub-millimeter waves. It is now possible to consider the interaction and control of intense THz waves with matter; investigate a single THz photon and explore its applications. In this project, we propose to generate coherent high-power THz radiation in order to explore topics in THz nonlinear and quantum photonics. The energy of generated THz pulses is expected to be above 0.3 mJ at a repetition rate of ~ 15 MHz.

The university also provides matching fund for supporting the consortium on THz Science and Technology, led by the applicant.

7. Patents granted and pending

- Ci-Ling Pan, Chan-Shan Yang, Tsung-Ta Tang, Ru-Pin Pan, Peichen Yu), “ [Liquid Crystal Based Optoelectronic Device](#),” US patent published, No. 2015/0253627 A1, Sept. 10, 2015, Taiwan (ROC) patent published, No. 201535026, Sept. 16, 2015.
- Ci-Ling Pan, Chan-Shan Yang, Ru-Pin Pan, Cho-Fan Hsieh, Fang-Cih Shih, “Tunable terahertz achromatic wave plate and a terahertz achromatic range tuning method,” Taiwan (ROC) patent filed, No. 105122124, US patent filed, No. I4P105065-US, Jul. 13rd, 2016.

8. News / Report:

As part of the commemoration of the 50 th anniversary of the founding of the journal, IEEE Journal of Quantum Electronics (JQE in Short), the editorial staff assembled a list of the downloaded article from each year’s publication. The list spans the years from 1965 to 2014. Download counts are equal to the total number of IEEE Xplore full article PDF downloads since tracking began in January 2011 through December 2014. The article by our group, entitled “Frequency-dependent complex conductivities and dielectric responses of indium tin oxide thin films from the visible to the far-infrared”, published in 2010 [1] was the most downloaded JQE article published that year, with 1043 downloads, of the 50 articles, this paper was ranked 24th. (see IEEE J. Quantum Electron vol. 51, NO.2, art.0400202, Feb., 2015, DOI: [10.1109/JQE.2015.2397672](#))

[1]Ching-Wei Chen, Yen-Cheng Lin, C. H. Chang, Peichen Yu, Jia-Min Shieh, and Ci-Ling Pan\*, “Frequency-dependent complex conductivities and dielectric responses of indium tin oxide thin films from the visible to the far-infrared,”



[IEEE J. Quantum Electron., Vol. 46, No. 12, pp. 1746-1754, December 2010.](#)

IEEE Xplore Link:

<http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7031994>

## 9. Committee Activities

### 2014

- Member, Program Committee, Emerging Liquid Crystal Technologies VII, Part of the SPIE International Symposium on Integrated Optoelectronic Devices 2014, Photonics West 2014 (SPIE), 1-6 February 2014, San Francisco, California, USA.
- Member, Technical Program Committee, 2014 IEEE TENSYP - IEEE Region 10 Symposium (TENSYP'14), Kuala Lumpur, Malaysia, April 14-16, 2014.
- **Convenor, Session on THz Communication, The XXXIst General Assembly and Scientific Symposium (GASS) of the International Union of Radio Science (Union Radio Scientifique Internationale: URSI), Beijing, China, August 17-13, 2014.**
- Member, Technical Program Committee, 5<sup>th</sup> International Conference on Photonics, Palace of the Golden Horse, Kula Lumpur, Malaysia, Sept. 2-4, 2014.
- Member, international advisory committees, OSA representative to The International Symposium on Physics and Application of Laser Dynamics (IS-PALD 2014), September 2-4, Hsinchu, Taiwan.
- Member, Technical Program Committee, PA111: Infrared, Millimeter-Wave, and Terahertz Technologies III, part of SPIE/COS Photonics Asia, October 9-11, 2014, Beijing, China.
- Co-Chair, Sub-Conference on “Quantum electronics”, Optics & Photonics Taiwan, International Conference 2014, Taichung, Taiwan, December 3-5, 2014.

### 2015

- Member, Program Committee, Emerging Liquid Crystal Technologies VII, Part of the SPIE International Symposium on Integrated Optoelectronic Devices 2015, Photonics West 2015 (SPIE), 7-11 February 2015, San Francisco, California, USA.
- Member, International Organizing Committee, Joint International Symposium of 3<sup>rd</sup> Microwave/THz Science and Applications (MTSA) and 6<sup>th</sup> Terahertz Nanoscience (TeraNano-VI), Okinawa, Japan, June 30-July 4, 2015.
- Member, Technical Program Committee, 40<sup>th</sup> International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz 2015), 23-28 August 2015, The Chinese University of Hong Kong, Hong Kong.
- Member, Technical Program Committee, 8<sup>th</sup> International Cnference on Advanced Infocomm Technology (ICAIT2015), Hanzhou, China, October 26-28, 2015.
- Co-Chair, Track 1 Optoelectronic Materials, Devices, and Integration, Asia Communications and Photonics Conference (ACP 2015), Nov. 18-23, Hong



Kong.

- Honorary Chair, Optics and Photonics Taiwan, International Conference (OPTIC 2015), Dec. 4-6, Hsinchu, Taiwan.
- Chair, 2015 Taiwan THz Workshop (T-TW 2015), a Satellite Conference of OPTIC 2015, Dec. 4-6, 2015, Hsinchu, Taiwan.

2016

- Member, Program Committee, Emerging Liquid Crystal Technologies VII, Part of the SPIE International Symposium on Integrated Optoelectronic Devices 2016, Photonics West 2016 (SPIE), 7-11 February 2016, San Francisco, California, USA.
- Member, International Program Committee for the EMN Meeting on Terahertz, May 15-18, 2016, San Sebastian, Spain
- Member, Advisory Committee, International Symposium on Physics and Applications of Laser Dynamics, 2016, Sep. 7-9, 2016, National Tsing Hua University, Hsinchu, Taiwan.
- Member, Technical Program Committee, 41th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz 2016), Sep. 25-30, 2016, Bella Center, Copenhagen, Denmark.
- Member, Program Committee, the 8th International Symposium on Ultrafast Phenomena and Terahertz Waves, October 10-12, Chongqing, China.
- Member, Program Committee, Infrared, Millimeter-Wave, and Terahertz Technologies IV, Photonics Asia (SPIE), October 12-14, 2016.